A Model of Seasonal Variability in the Indonesian Archipelago

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LONG-TERM GOALS

The ultimate goal is to quantitatively understand factors determining the circulation within and through the Indonesian archipelago on a range of time-scales, and so evaluate how best to 'parameterize' the archipelago in multi-level, finite-difference, ocean general circulation models used in forecasting, which cannot resolve the archipelago's thousands of small islands and straits.

OBJECTIVES

This year's objectives were to construct semi-analytical process models of the variability in transport and water-mass composition within and through the Indonesian archipelago, and investigate:

1. Whether there is variability in throughflow composition on interannual timescales and longer , and if so, what is the nature of the variability and its cause, and if not, what additional processes need to be incorporated into Wajsowicz's (1993) simple model to suppress the composition variability implied by the variability in the Pacific's wind stress curl. (Sorting out discrepancies in the climatological mean composition, which had surfaced between models forced by different wind-stress data sets, was considered essential before tackling the task of seasonal variability.)

2. Whether mesoscale variability in the wind-stress curl over the southeast Asian seas is important in determining annual cycle transports, and how sensitive the annual mean and annual cycle transports are to wind-stress data set.

APPROACH

The model for water-mass composition is based on the analytical, 2-D streamfunction model of Wajsowicz (1993), which is extended to include prescribed nonlinearity and an arbitrary number of straits in parallel and series.

The transport model is based on the semi-analytical, multiple-island-rule model of Wajsowicz (1998), which is reconfigured for fine- and coarse-resolution geometries. The wind stress data sets used to force the models are constructed from $0.5^\circ \times 0.5^\circ$ gridded satellite products, namely SSM/I and NSCAT.

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WORK COMPLETED

1. Throughflow Composition: Surface wind fields from SSM/I data on a 0.5° x 0.5° grid were obtained from Dr. R. Atlas' group at NASA/Goddard Space Flight Center, Atlas et al. (1996). These data were put through some extra quality controls, and a wind stress data set for 1986-1994 produced. The data were averaged onto a 2.5° x 2.5° grid to produce a second data set. Sverdrup streamfunctions were calculated for both the fine and coarse resolution data, and the implied Indonesian throughflow composition, using Wajsowicz's (1993) analytical model, calculated. Similar calculations were also repeated for the nine months of NSCAT data available.

The analytical model of Wajsowicz (1993) was reformulated in terms of channel operators to generalise the solution to an arbitrary number of successive channels. The parameter space for configurations representing possible choices of archipelago geometry in a GCM were explored. The model was further extended to include overshooting of the Mindanao Current and South Equatorial Current, and the Halmahera and Mindanao Eddies, as 'features'. The impact of these features on the throughflow composition was investigated.

The throughflow compositions for varying degrees of nonlinearity in the western boundary currents and for timescales from interannual to interdecadal, were calculated using wind stress data from FSU (1961-1998), ECMWF (1987-1995), SSM/I (1986-1994). Historical salinity data archived at the National Oceanographic Data Center, Washington, D.C. (NODC), was obtained and analysed for trends suggested by the new composition model forced by FSU wind stress data for 1961 to 1998. The new model and findings were written up for publication and submitted to JPO, Wajsowicz (1999).

2. Annual Cycle in Transports Within the Indonesian Seas: The multiple-island-rule model of Wajsowicz (1998) was recast on a 0.5° x 0.5° grid and a 2.5° x 2.5° grid. The fine- and coarse-resolution SSM/I and NSCAT data, described above, were used in conjunction with the appropriate multiple-island-rule models to calculate the annual cycle in transports within the Indonesian seas. The resulting Sverdrup streamfunctions were also calculated and compared with TOPEX altimeter data.

RESULTS

1. Throughflow Composition: Wajsowicz's (1993) analytical model gives that the throughflow is of wholly South Pacific origin if the streamfunction is positive at the interior edge of the Pacific western boundary layer at the northern tip of Irian Jaya. It is wholly of North pacific origin if the streamfunction is negative and greater in magnitude than the throughflow magnitude at this same point. The Sverdrup streamfunction derived from FSU wind stress data varies considerably at this latitude, which implies significant variability in throughflow composition. The data are only on a 2° x 2° grid, which may introduce further errors into the calculation. The analysis with fine and coarse resolution SSM/I wind stress data showed that the composition was effectively independent of grid resolution, but this was not because the wind-stress curl and its interannual variability were of large spatial scale. It transpired that the SSM/I data gave a dynamical regime in which the throughflow was wholly of North Pacific origin and there was very little interannual variability, which contrasted with earlier results using FSU wind stress data.
The suprising sensitivity of throughflow composition to choice of wind stress data set (FSU, ECMWF, SSM/I), with SSM/I and ECMWF completely at odds, suggested looking again at the analytical model

of Wajsowicz (1993) to see whether new effects could be taken into account, which would bring the three models closer together. Introducing overshooting of the western boundary currents, and the Mindanao and Halmahera Eddies, as features in the streamfunction field was found to be equivalent to shifting the effective SEC retroflection latitude, y_N, northwards, i.e. nonlinear effects can be included in Wajsowicz's (1993) analytical model by redefining the parameter y_N. This is an important, and very relevant, extension of the model as the further north from the equator the choice of y_N, typically the more negative the streamfunction, and so the greater the throughflow contribution from the North Pacific. Also the more northward y_N the less the latitude of a given streamline varies with time, and so the less temporal variability in the composition, which is in better agreement with the notion of observationalists. Understanding the significance of the Halmahera and Mindanao Eddies and overshooting of the western boundary currents, in turn better explains the significance of the NW-SE orientation of the Pacific western boundary over the equatorial latitudes, and the gap width of the entrance to the archipelago, as these determine the location of the Eddies.

Reformulating, by defining channel operators, and extending to an arbitrary number of successive channels, the simple, analytical model of Wajsowicz (1993) on throughflow composition, has led to a much better understanding of why the composition varies zonally over the archipelago, and the criteria, which determine the composition in each strait/sea of the archipelago. The model demonstrates the perverse conditions, which would need to exist in the Pacific to alter the observed composition of purely North Pacific water in Makassar Strait and South Pacific water in the Halmahera Sea. An example of the fractional composition in each of the major entrance channels to the archipelago given by the simple model is shown in Fig. 1. The streamfunction values are nondimensionalised on the value on Australia, whose magnitude gives the throughflow. Further details may be found in Wajsowicz (1999).

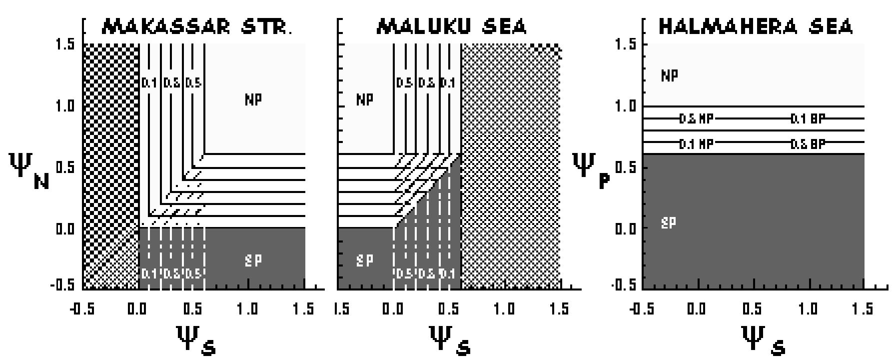

Fig.1: Fractional composition of the throughflow in each of the major entrance straits of the archipelago is contoured as a function of the streamfunction value on Sulawesi, ψ_S, and at the interior edge of the Pacific western boundary layer at the effective retroflection latitude, $y_{N,P}$, assuming the streamfunction takes the value 0.6 on Halmahera. The streamfunction has been nondimensionalised on the throughflow magnitude. NP (SP) denotes North (South) Pacific water mass with solid (dot-dash) contours and light (dark) shading.

Discussions are underway with Professor Gordon, LDEO, Columbia University on applying the three-channel (Makassar-Maluku-Halmahera) composition model to the ARLINDO data to explain the seasonal and interannual variability in observed transport and composition. Meantime, the model has

been used in conjunction with Florida State University wind stress data to explore possible decadal-scale variability in composition. The model predicts a shift to a more salty throughflow, and hence a fresher, western equatorial Pacific over the last thirty years, see Fig. 2. Analysis of historical salinity profile data from NODC, see Fig. 3, supports this finding.

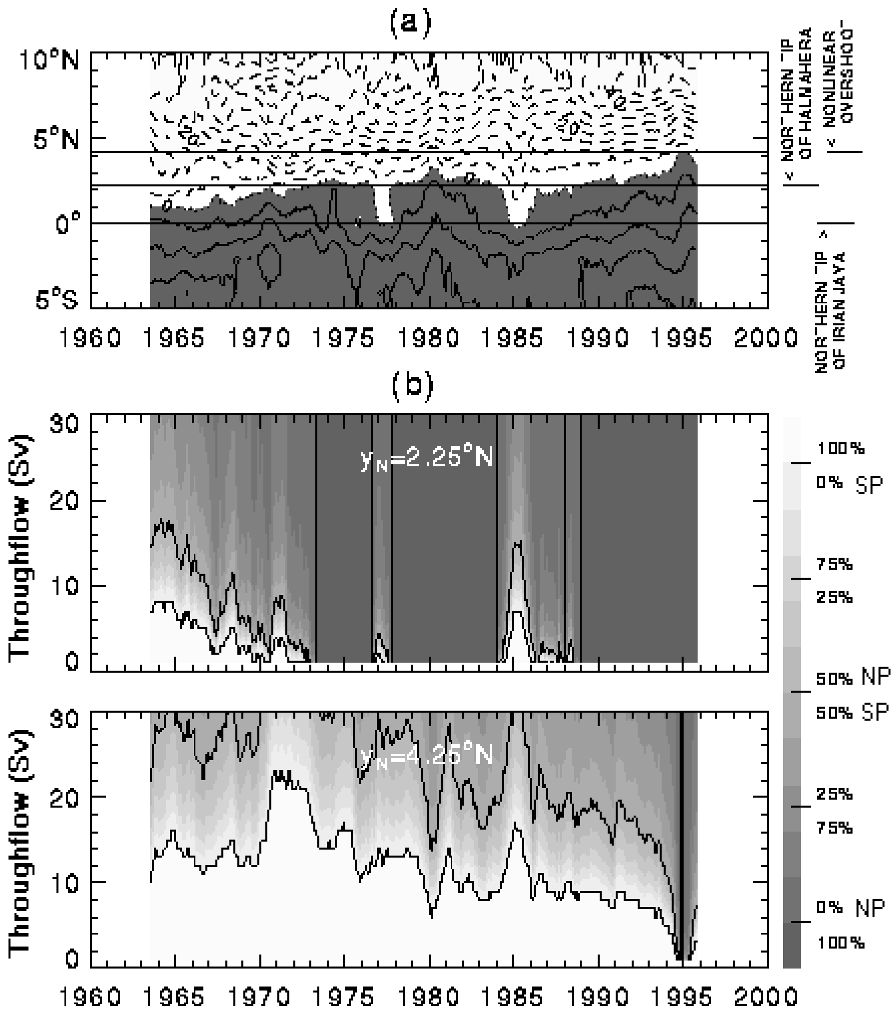

Fig. 2: The Sverdrup streamfunction at the interior edge of the Pacific western boundary layer is contoured as a function of time and latitude in (a) with a 5-year running mean applied. Possible effective retroflection latitudes, y_N, are marked. If the region shaded dark grey (ψ>0) penetrates north of y_N, then the throughflow is wholly from the South Pacific. It is wholly from the North Pacific if the region shaded light grey (ψ<-10Sv) penetrates south of y_N, where 10 Sv has been chosen as the throughflow magnitude for sake of illustration. The resulting throughflow composition from a single-channel model is contoured in (b) as a function of time and throughflow magnitude assuming the effective retroflection latitudes are the northern tip of Halmahera and 2^o of latitude further north.

2. Annual Cycle in Transports Within the Indonesian Seas: Wajsowicz (1998) compared the annual and semi-annual cycles in transports obtained in the Parallel Ocean Climate Model (POCM) of Prof. A.J. Setmner and colleagues, NPGS, Monterey with those obtained from a multiple-island-rule model forced by wind stress variations in different geographical regions. Agreement at semi-annual period was poor, as the Indonesian seas store heat locally on these timescales, which gives the appearance of a capacitor effect. At annual period, fairly good agreement was found if just wind-stress variability over the archipelgo were considered. Comparison between TOPEX altimeter data and POCM sea-level at annual period showed similar amplitude and phase, but the POCM signal was weaker. This suggested that there were mesoscale features in the wind stress over the southeast Asian seas, which enhanced the annual period transport variations, but that this mesoscale signal was not resolved by the interpolated $2.5^{o} \times 2.5^{o}$ ECMWF wind stresses used to force POCM. Both the NSCAT and SSM/I fine-resolution data sets show considerable mesoscale variability. At the time of writing this report, the impact on the annual period transports is still being considered, and a manuscript for possible publication in the Journal of Physical Oceanography is in preparation.

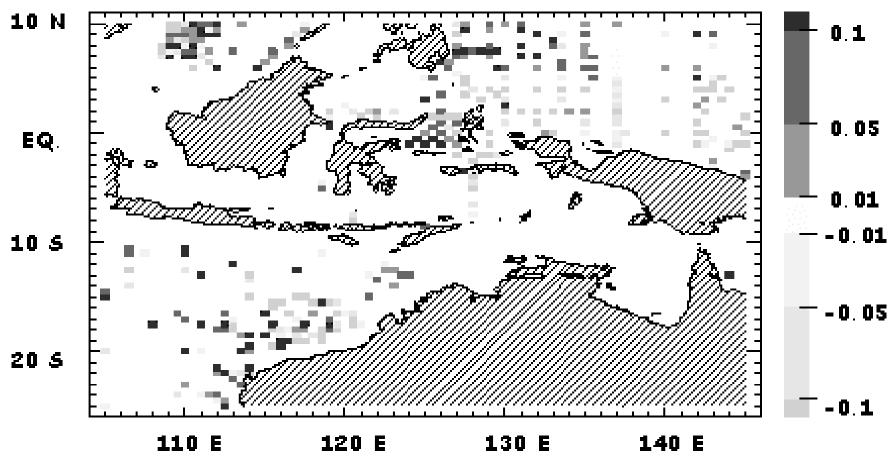

Fig. 3: The difference in salinity in units of ppt., integrated from 100 m to 300 m and averaged over the depth, between epochs 1966-1980 and 1981-1995 for the Indo-Pacific region is displayed. Salinities were obtained from WODB-98 profile data compiled by NODC. The seasonal bias in the observations has been removed.

IMPACT/APPLICATIONS

The development of sophisticated, numerical models for forecasting the ocean circulation and hydrographic state is a priority for ONR, as is knowledge and understanding of the ocean circulation in strategically important regions such as the Indonesian archipelago and other east Asian marginal seas.

TRANSITIONS

In general terms, my ONR-funded research provides a theoretical framework to support ONR's ongoing field program in the region (Gordon's ARLINDO and Sprintall et al.), and the numerical primitive-

equation modeling research at NRL, Mississippi (Hurlburt, Kindle and Preller) and NPGS (Semtner, Tokmakian and McClean). As noted previously, important findings have been made of interest to the GOALS/CLIVAR community. Preprints of my manuscripts 'Models of the Southeast Asian Seas' and 'Variations in Gyre Closure ....' have been widely circulated and well received. Major new results, which contradict previous wisdom, have been impactful. For example, the ECMWF Coupled Modelling Group had beeen trying for several months to solve the problem of the wrong throughflow source by fruitlessly modifying the topography. My research has answered many of their questions and provided information on how best to redirect their effort.

Professor Arnold Gordon, LDEO, Columbia University is using results from my papers to help in interpretation of ARLINDO data. Professor Roger Lukas, SOEST, University of Hawaii, is using the results to help formulate plans for observing the southeast Asian monsoon system as part of the CLIVAR program.

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